AN EXPERIMENTAL INVESTIGATION OF ELECTRICAL DISCHARGE MACHINING USING REVERSE POLARITY

by

Hans C. Juvkam-Wold

S.B. Massachusetts Institute of Technology
(1966)

Submitted in partial fulfillment
of the requirements for the
degree of Master of Science

at the

Massachusetts Institute of Technology

August, 1967

Signature of Author ....
Dept. of Mechanical Engineering, August 21, 1967

Certified by ....
Thesis Supervisor

Accepted by ....
Chairman, Departmental Committee
on Graduate Students

AN EXPERIMENTAL INVESTIGATION OF ELECTRICAL DISCHARGE MACHINING USING REVERSE POLARITY

by

Hans C. Juvkam-Wold

Submitted to the Department of Mechanical Engineering on August 21, 1967 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

The principal purpose of this investigation was to determine experimentally the parameters governing electrical discharge machining (EDM) under conditions of reverse polarity (tool positive). Tool steel was machined on an Elox EDM machine using graphite and copper electrodes (tools). The frequency was varied from 0.34 kc to 63 kc, the duty cycle from 30% to 80%, and the current from 1 to 115 amps.

The wear ratio (tool/work) was found to increase with frequency and to decrease with duty cycle and with current. It was found that the wear ratio is correlated with the magnitude of the overcut, which in turn is controlled by the size of the particles (usually hollow spheres) eroded from the workpiece during each pulse of electrical energy.

The metal erosion rate from the workpiece was found to be proportional to the 0.85th power of the current when graphite electrodes were used. At a current of 35 amps, the maximum erosion rate of 0.022 cubic inches per minute was obtained at a frequency of 9 kc and 65% duty cycle.

The graphite tools consistently gave higher erosion rates and lower wear ratios than those obtained using copper tools.

A qualitative theory of the erosion mechanism is suggested and examined in the light of the experimental data.

Thesis Supervisor: Robert E. Stickney
Title: Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I wish to thank Professor R. E. Stickney for suggesting this research topic and for his guidance and encouragement throughout. I also wish to thank Mr. T. Viswanathan for making the runs with copper electrodes, and Mrs. Rose Hurvitz for her expert typing of the manuscript. My understanding of the EDM process has been greatly enhanced through discussions with my fellow students: De Nigris, Doret, Weetman, and Viswanathan. These discussions have been invaluable.

Further I wish to thank the Elox Corporation of Michigan for supplying the EDM machine and power supply, and for giving advice and helpful suggestions on a number of occasions.

I also wish to express my deep appreciation to Mene Grande Oil Company (Gulf) for four and a half years of continuous fellowship support. Finally, I wish to thank the Research Laboratory of Electronics for supplying me with an RLE fellowship during this last summer.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The erosive effect of electric sparks has been known for over 200 years. During the last quarter century a machining process making use of this effect has been developing. This process, known as electrical discharge machining (EDM) consists essentially of passing successive pulses of electrical energy between two electrodes, the tool and the workpiece, and gradually eroding the latter to any desired configuration. A concise description of the process is given by Cook[1] and an extensive evaluation by Berghausen et al.[2] EDM has many advantages over conventional chip machining, and is particularly useful where intricate shapes or very hard materials are to be machined. Since the tool need never be in physical contact with the workpiece, it can be made from some easy-to-shape soft material like graphite, which incidentally has outstanding wear characteristics, and any conducting material can be machined, irrespective of hardness.

In spite of the importance of EDM today, the basic principles underlying the process are far from being fully understood. Until this handicap is overcome, the process cannot be developed to its full potential. A systematic approach to this problem is now well under way here in the Mechanical Engineering Department at M.I.T., and this thesis is the second of a series.

As indicated above, tool wear is a matter of great importance, since tool replacement is a major operating expense. Under standard polarity EDM, the workpiece is the positive electrode (anode), but experience has recently shown that under certain operating conditions, tool wear can be substantially reduced, and sometimes almost completely eliminated, by reversing the polarity of the electrodes, thereby making the tool be the anode. The purpose of the present investigation is to determine empirically the parameters governing machining performance of EDM under conditions of reverse polarity. Particular emphasis is placed on determining the wear ratio (the volume of material worn away from the tool per unit volume of material eroded from the workpiece), and the machining or erosion rate of the workpiece, under different operating conditions. By observing the conditions under which different tool wear is obtained, it should be possible to understand better the wear mechanism, and in turn to extend the region of low tool wear.

In Section 2 of this thesis the apparatus is described. Also the experimental procedure is described in some detail.

The experimental results are presented in Section 3, and each graph is briefly described. An attempt has also been made to explain the results, but this is left until Section 4. The independent variables are the frequency of the electric pulses,the duty cycle (the ratio of the time that the power is on to the total period of each pulse, expressed as a percentage), the average current, and the tool material. The most important dependent variables are wear ratio and erosion rate (in this report the latter expression always refers to the workpiece).

Section 4 contains a general discussion of the results, and a provisional theory is presented in an attempt at explaining the results. The limitations of this theory should be emphasized, and may not be valid under conditions different from the ones tested here.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus consists essentially of an EDM machine, a power supply, miscellaneous measuring devices, and an oscilloscope. A schematic of the setup is shown in Fig. 1.

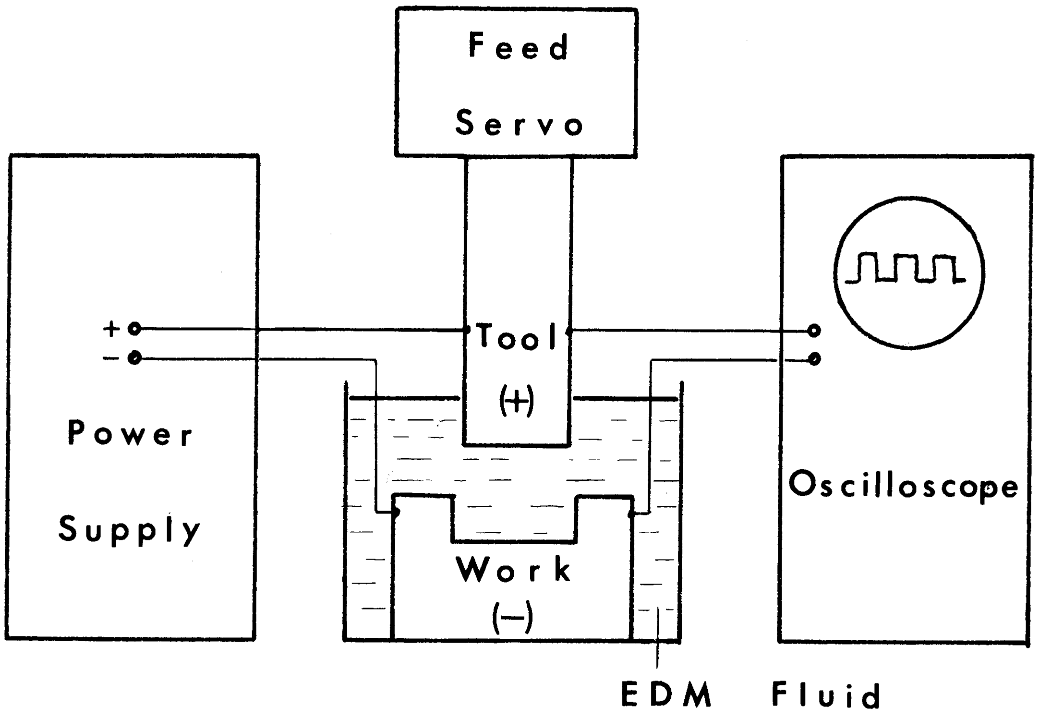

Fig. 1. Schematic view of experimental apparatus under reverse polarity conditions.

2.1. Electrical Discharge Machine

The EDM machine used in these experiments is an Elox HRP-63 unit. This is a rigid and accurate machine. The workpiece is located inside a workpan, under at least three inches of EDM fluid (ofter called the "dielectric"; in this case Eloxol #13 was used throughout). The tool is attached to a ram whose vertical motion is controlled by a servomechanism which in turn is controlled by the electrode gap (the distance between the tool and the workpiece). The machine also has a pump and filter for providing a constant supply of clean EDM fluid to the electrode gap. Another pump is provided for quick filling of the workpan.

2.2. Power Supply

Square voltage pulses are supplied from an Elox SSD 400 NW experimental power supply. This unit can supply pulses at frequencies from 0.34 kc to 170 kc, and currents up to 400 amps. The duty cycle (percent ON-time) can be varied continuously from about 8% to 90%. The power supply also controls the feed rate of the servomechanism, and permits some variation of the electrode gap.

2.3. Tool and Workpiece Description

The geometry of the tool and workpiece is shown in Fig. 2. The tool is a cylindrical rod of 0.75-inch diameter. The workpiece is

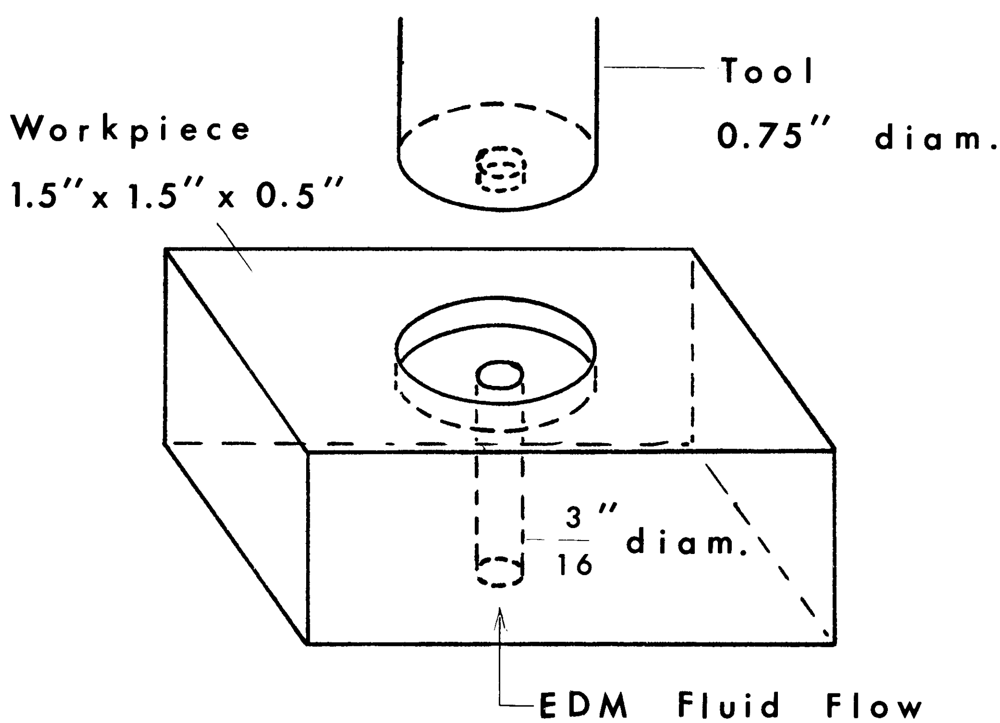

Fig. 2. Geometry of tool and workpiece

1.5"x 1.5"x 0.5", and has a 3/16" hole drilled at the center to permit the flow of coolant (EDM fluid). This geometry was chosen because of the cylindrical symmetry which permits good flushing and simple analysis.

The material of the workpiece is tool and die steel, H-13, produced by the Carpenter Steel Company under the number 883. Both hardened and unhardened steels were tested, with surprisingly little difference in performance. Three kinds of tool material were tested: (1) 99.9% pure copper; (2) Kost Kutter No. 8; and (3) Kost Kutter No. 12. The last two types are commercial graphite EDM electrodes produced by the Speer Carbon Company. KK #8 is a standard electrode material, and KK #12 is somewhat harder and stronger, and is specifically recommended by the producers where fine detail on the electrode is desired.

2.4. Measurement of Tool Wear and Workpiece Erosion

The linear wear on the tool and on the workpiece were measured at four different points around the circumference of a circle of radius 1/4" and axially centered. An Ames No. 384 dial gauge, correct to 0.0005", was used. As very little rounding off of the edges of the electrodes occurred, the volume of material removed was obtained by multiplying the linear wear by the cross-sectional area (0.415 in^2).

The overcut was taken to be half the difference between the diameter of the hole eroded in the workpiece and the final diameter of the tool. For these measurements a Helios inside-outside vernier caliper, accurate to 0.001", was used. Again an average of four readings was taken. Some of these readings were later checked using a screw-type Fowler micrometer.

2.5. Determination of Gap Voltage, Frequency, and Duty Cycle

The variation of voltage (V) across the electrode gap with time (t) was observed on a Tektronix Type 511A Cathode Ray Oscilloscope (Fig. 3).

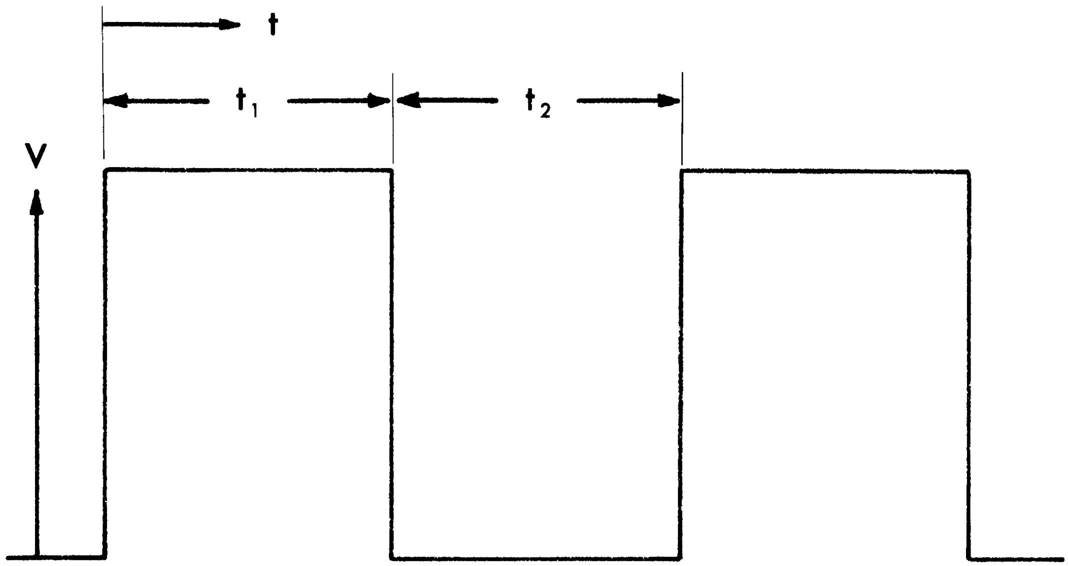

Fig. 3. Variation of voltage across the electrode gap when the unit is not machining, as observed on the oscilloscope.

The frequency of the pulses is simply the reciprocal of the total time per pulse $\left(\text{frequency} = \frac{1}{t_1 + t_2}\right)$. The duty cycle, which is defined to be the percentage ON-time, can also be obtained from the oscilloscope $\left(\text{duty cycle} = \frac{t_1}{t_2} \times 100\%\right)$. The oscilloscope sweep speed was calibrated using a Tektronix Type 181 Time-Mark Generator, accurate to 0.01%.

2.6. Current Measurement

The machining current was measured with a Weston D.C. ammeter connected across an external shunt. This ammeter was calibrated against a Hewlett Packard Model 412A DC Vacuum Tube Voltmeter, and also against a Tektronix Type 536 Oscilloscope. The readings on the ammeter were never off by more than 1.5%. The currents mentioned in this report are taken directly from the ammeter.

3. EXPERIMENTAL PROGRAM: OBJECTIVES AND RESULTS

3.1. Outline of Experimental Program

The overall purpose of this program was to enhance our understanding of the EDM process, in an attempt at improving the performance of the process. It was felt that this could best be achieved through an empirical investigation of the parameters which influence wear ratio and machining rates.

The "standard" test was chosen to be a frequency of 9 kc, a duty cycle of 50%, and a current of 35 amps. Hence, when the dependence of wear ratio and erosion rate on frequency was to be determined, the duty cycle was kept constant at 50%, and the current at 35 amps. Similarly, the dependence on duty cycle was investigated at 9 kc and 35 amps, and so on. 9 kc was chosen because near this frequency the maximum erosion rate of material from the cathode is obtained. In addition, sufficient wear is obtained on the tool to allow fairly accurate measurement of this wear. 50% duty cycle was chosen because this value was obtainable from the power supply over a wide range of frequencies, from 0.34 kc to 34 kc. Barring this, a higher duty cycle would have been preferred, but 77% was obtainable only up to 9 kc. A current of 35 amps was arbitrarily chosen, and was easily realizable over most of the spectrum tested. However, a lower current, about 20 amps, would have been obtainable over an even larger range of conditions.

Graphite is probably the most popular EDM tool material in use today, but considerable amount of work has also been done with copper. For this reason two commercial graphite EDM electrodes, and also pure copper, were chosen for these experiments. Another reason for choosing copper is that visual observation of the erosion craters and material deposits is much easier on copper than on graphite.

Any material which will conduct electricity can be machined by EDM, but since it was impossible in the time available to test all the materials that fall into this category, the choice was narrowed down to a hard substance that is often machined by EDM, and tool and die steel, H-13, was chosen.* Both hardened and unhardened H-13 were tested.

3.2. Experimental Results

The wear ratio (tool/work) increases with increasing frequency, and decreases with increasing duty cycle or increasing current.

Figure 6 shows the dependence of wear ratio on frequency. For a current of 35 amps and a duty cycle of 50%, and for frequencies between 0.34 kc and 63 kc, the following results were obtained: with a graphite tool, the wear ratic is proportional to the 0.8th power of the frequency; and with a copper tool, the wear ratio is proportional to the 0.14th power of the frequency. That is,

$$\text{graphite tool: (wear ratio)} \sim \text{(frequency)}^{0.8} \quad (1)$$

$$\text{copper tool: (wear ratio)} \sim \text{(frequency)}^{0.14} \quad (2)$$

Over the whole range investigated, graphite gives a lower wear ratio than copper, although if the trends indicated on the graph (Fig. 6) continue to much higher frequencies, then copper would give a lower wear ratio than graphite at frequencies above 250 kc.

The relationship between wear ratio and duty cycle is shown in Fig. 7. At a frequency of 9 kc and a current of 35 amps, the following results were obtained: With a graphite tool, for duty cycles between 30 and 80%, the wear ratio decreases as the log of the duty cycle increases:

$$\text{graphite tool: (duty cycle)} = 100 \exp[-\ 14.4\text{(wear ratio)}] \quad (3)$$

With a copper tool under the same conditions, the wear ratio increases slightly with duty cycle between 30% and 50%, but for duty cycles between 50% and 80%, the wear ratio decreases with increasing duty cycle.

Figure 8 shows that at a frequency of 9 kc and a duty cycle of 50%, the wear ratio decreases with increasing current, for currents between 1 and 100 amps. This holds both for graphite and copper tools. This relationship is again logarithmic and may be expressed as follows:

---

*Currently in progress is a study to investigate the effect of different workpiece materials by T. Viswanathan, research assistant, M.I.T.

$$\text{graphite tool: (current)} = 140 \exp[-29(\text{wear ratio})] \quad (4)$$

The wear ratio decreases exponentially with increasing overcut $[\frac{1}{2}(\text{hole diam.} - \text{tool diam.})]$ (Fig. 9). At a current of 35 amps, for frequencies between 0.34 kc and 63 kc, and for duty cycles between 30% and 80%, the following relationships hold approximately:

$$\text{graphite tool: (wear ratio)} = 0.6 \exp[-690(\text{overcut in inches})] \quad (5)$$

$$\text{copper tool: (wear ratio)} = 0.8 \exp[-160(\text{overcut in inches})] \quad (6)$$

As shown in Fig. 10, the overcut is proportional to the cube root of the volume of cathode material eroded per pulse.

$$\text{For all conditions tested: (overcut)} = 5.8(\text{volume eroded})^{1/3} \quad (7)$$

where overcut is measured in inches, and volume eroded is measured in in^3/pulse.

Note that this relationship holds for all frequencies between 0.34 and 63 kc, duty cycles between 30 and 80%, currents between 1 and 100 amps, and for both graphite and copper tools, i.e., it holds under all conditions investigated in this program!

As the volume of material eroded from the workpiece per pulse becomes larger, the wear ratio decreases, and may even go negative. This fact is shown in Fig. 11. The data points on this graph do not follow any simple equation.

The erosion rate of material from the workpiece increases with increasing frequency, goes through a maximum, and then decreases again (Fig. 12). These experiments were carried out at a current of 35 amps and a duty cycle of 50%. For copper electrodes the optimum frequencv appears to be about 1-8 kc, and the erosion rate decreases quite significantly at frequencies below 1 kc or above 20 kc. With graphite electrodes the maximum erosion rate was obtained between 4 and 14 kc, and highly reduced rates were obtained for frequencies below 2 kc or above 20 kc.

Most of the experiments discussed in this report were carried out using unhardened steel H-13 as workpiece material. However, a number of runs were made using KK #8 tool and hardened steel H-13 workpiece. Under most experimental conditions slightly lower erosion rates and slightly lower wear ratios were obtained with the hardened H-13. However, at frequencies below 4 kc, significantly lower erosion rates are obtained, as shown in Fig. 12. Near 9 kc the difference is very small, and as all the other tests in the program were carried out at this frequency, the data points with hardened and unhardened steel can be mixed without increasing the scatter significantly, except in Fig. 13. More details regarding this matter can be found in the data tables in Appendix A, Tables 1-a and 1-b.

In Fig. 13 the dependence of workpiece erosion rate on duty cycle at 9 kc and 50% duty cycle is shown. There is little variation, except for a reduced rate at very low or (in the case of hardened steel workpiece) at very high duty cycles.

At a frequency of 9 kc and a duty cycle of 50%, the erosion rate increases with current over the whole range tested (Fig. 14). For currents between 7 and 70 amps the following equations hold:

$$\text{graphite tool: (erosion rate)} \sim \text{(current)}^{0.85} \tag{8}$$

$$\text{copper tool: (erosion rate)} \sim \text{(current)} \tag{9}$$

Currents above 70 amps could not be obtained with graphite tools. With copper as tool material, a substantial reduction in the rate of increase of erosion rate with current is obtained above 70 amps.

Another way of presenting the erosion data is often used, so in Fig. 15 the erosion rate, in units of $\left(\frac{10^{-4}\ \text{in}^3}{\text{amp.min}}\right)$ is plotted against current. The erosion "efficiency",as it might be called, is seen to decrease with increasing current in the case of graphite tools. With copper as tool material, this erosion "efficiency" is essentially constant up to about 60 amps, after which it falls off significantly.

In order to check the dependence of the erosion rate on the depth of cut, a couple of runs were made. The results speak for themselves (Fig. 16). For a depth of cut less than 0.4" the erosion rate is substantially constant.

4. DISCUSSION OF RESULTS

4.1. Theoretical Background

In order to explain fully the experimental results obtained in this investigation, it is essential to give some theoretical background. No attempt is made here to survey all the theories related to EDM. Instead a selection of theories which tend to support our experimental results is given.

We here suggest that the wear of the tool (anode) is determined by the size of electrode gap. One reason for this is that the stream of electrons that leaves the cathode, gradually spreads out due to electron repulsion and electron diffusion, as shown in Fig. 4. This is by no means a novel idea, and has been suggested by Ullmann,[3] Webb,[4] and others. Hence, as the gap spacing is increased, the area of the anode spot also increases, so that for a given total current the power density becomes less. When the power density is low enough, the ON-time is not sufficiently long to raise the temperature of the tool surface up to the melting point, and no wear results by this mechanism.

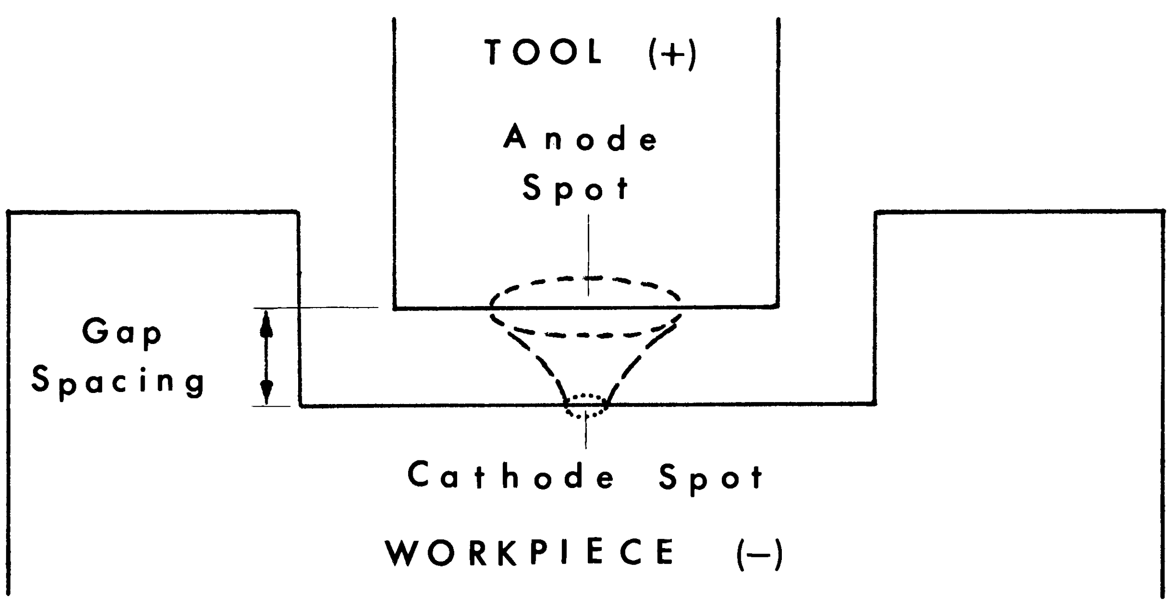

Fig. 4. The anode spot size increases with gap spacing.

Mandel'shtam and Raiskii[5] suggest that the anode surface is eroded by "vapor jets" emitted from the cathode surface, and the cathode is similarly eroded by smaller jets from the anode. They find that by increasing the electrode gap the wear on the anode decreases, and at large enough spacings the anode becomes plated with material from the cathode. This method of wear from the anode appears to be correct, but the erosion from the cathode is probably predominantly caused by positive ion bombardment. Kesaev[6] sums it up as follows:

> "... Thus, it may be seen that the cause of electrode erosion is the predominantly thermal and mechanical effect exerted on the electrodes by the charged [ions] and neutral [vapor jets] particles moving at high velocity in the discharge gap."

Combining these ideas, we suggest that the anode wear mechanism consists primarily of vapor jets emitted from the cathode, a mechanism whose efficiency decreases with increasing gap distance; whereas the cathode is eroded primarily by positive ions which are accelerated in the cathode fall (a potential drop of the order of 10 volts, very close to the cathode surface), a mechanism in essence independent of electrode spacing. The energy balance at the cathode is thus of great importance for determination of the erosion rate at the cathode (workpiece), but this subject has been discussed in detail by Holm,[7] Somerville,[8] Kesaev,[9] and others, so it will not be repeated here.

To summarize the above, when the electrode spacing increases, the anode wear definitely decreases, whereas the cathode wear remains essentially constant.

Before going on to see how the above theories can explain the experimental results, we shall define some terms that will be used later. To do this, let us take a look at the picture on the oscilloscope (Fig. 5) when the machine is operating. Line 1 shows voltage pulses that do not break down the gap. Line 2 shows a broad band of pulses that do break down the gap. The height of line 2 represents the instantaneous voltage across the gap. This voltage, V_2, multiplied by the instantaneous current (peak current), I_{max}, gives the instantaneous power during the pulse. The total energy per pulse is $V_2 I_{max} t_1$, where t_1 is the ON-time of the pulse.

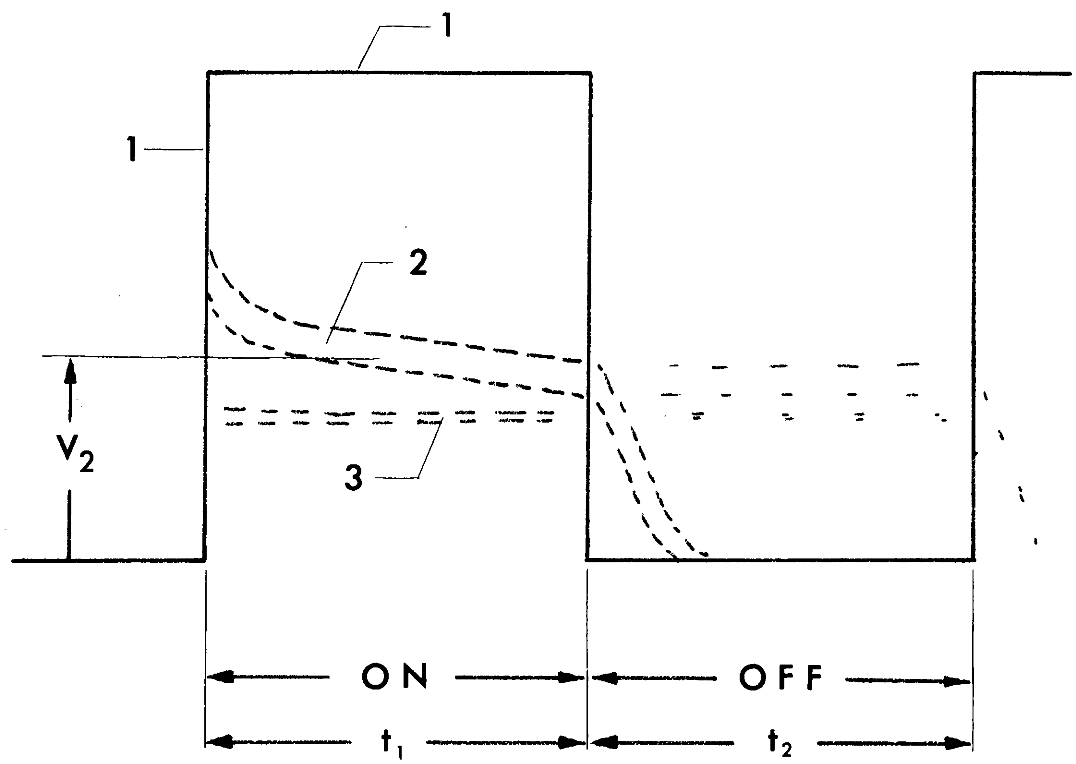

Fig. 5. Picture on the oscilloscope under good machining conditions.

Of this energy, some goes to the cathode, some to the anode, and some to the EDM fluid. The instantaneous power reaching the anode, divided by the area of the anode spot (Fig. 4), gives the instantaneous power density at the anode surface. The average current is the current that is read on the D.C. ammeter. This current multiplied by V_2 gives approximately the average power put out by the power supply.

4.2. Conditions Determining Wear Ratio

4.21. Frequency

As the frequency is lowered, each spark erodes more material from the cathode (workpiece) but less material from the anode. At first this may seem contradictory, but these results can be explained. When larger particles are removed from the cathode (because of higher energies per pulse), the overcut becomes larger because these particles have to be washed out of the hole being drilled. If the overcut is not sufficiently large, then breakdown will occur between the side of the tool and the side of the hole in the workpiece, through the particle. These same large particles will similarly cause the electrode gap to be larger, probably of the same order of magnitude as the overcut, and definitely proportional to the overcut. But when the electrode gap is larger, the power density at the anode becomes less since the arc has a chance to spread out considerably due to electron repulsion. Hence, the anode surface is heated up less, and may not reach the melting point of the tool material.

The above theories claim that the wear on the anode is caused by "vapor jets" of material ejected from the cathode at high velocities. At low spacings (high frequencies) the vapor jets will wear down the anode, whereas at larger spacings (lower frequencies) the molten metal tends to plate onto the anode rather than wearing it down. This is why we get such low wear ratios at low frequencies (Figs. 6, 17, and 19), because the steel from the cathode now protects the tool surface. At higher frequencies, and hence lower spacings, very little protection is offered (Figs. 6, 18, and 20). De Nigris[10] has calculated the time required to wear away such a protective layer at an assumed incident power density of 10^6 watts/cm^2.

From the above discussion it should be clear why the wear ratio increases with frequency.

4.22. Duty Cycle

The wear ratio decreases with increasing duty cycle. At the present time it is not quite clear why this should be so. The current is kept constant, so the power input is constant. This gives a constant energy per pulse, so the size of the particles removed from the cathode, and hence the gap distance, should be constant. This should, in turn, give a constant wear ratio. One possibility is that a long pulse might remove more material than a shorter pulse of equal energy, but then the erosion rate should increase consistently with duty cycle, and this is not so, as Fig. 13 shows. Another possibility is that the machinability (the fraction of the total number of pulses put out by the power supply that actually do break down the gap) decreases with duty cycle. Then, in an effort to maintain a constant average current, the peak current during the pulses which do break down the gap becomes higher, so more energy is supplied for each effective pulse. The particles removed are now larger, and hence the wear ratio lower, thereby explaining the shape of the curve. Yet another possibility is suggested by the picture on the oscilloscope (Fig. 5). Line 2 sometimes extends across the OFF-time as well, and apparently this could be due to the arc not being extinguished after each pulse. Then, for these pulses twice as much energy (or more) goes into each one, so much larger particles are removed, thereby giving large spacings and low wear ratios. As the duty cycle increases, the OFF-time gets shorter and shorter, so it seems reasonable to assume that more and more of the arcs would fail to extinguish, thus bringing about the decrease in wear ratio that Fig. 7 shows. However, the last suggestions are purely speculative and must be supported or denied by further experimentation. One shred of evidence is given by the fact that, in general, the overcut appears to increase with duty cycle (Appendix A, Table 1-a). This is not positively shown by the data, however, and will not be until a more accurate way of measuring the overcut is developed.

4.23. Current

For currents up to 70 amps the wear ratio decreases with increasing current, both for graphite and for copper tools (Fig. 8). Qualitatively similar results were obtained by Livshits et al.[11] but the conditions of their experiments were not fully specified, so a direct comparison is impossible.

The reason for the relationship shown in Fig. 8 is that at higher currents the energy per pulse is higher. This causes larger particles to be removed from the workpiece, so the gap spacing is larger, and hence the tool wear and wear ratio are lower.

4.24. Tool Material

As mentioned earlier, graphite has considerably better wear characteristics than copper, over the whole range of conditions included in Figs. 6 through 8. Graphite KK #12 gives a very slightly lower wear ratio than KK #8 but this difference is almost insignificant.

At 50% duty cycle, copper has a wear ratio of more than 0.2, even at the lowest frequencies tested (0.34 kc). By increasing the duty cycle to 80% and keeping the current at 15 amps, essentially no wear is obtained on the copper tool at frequencies below 1 kc (tests made by Elox Corporation of Michigan).

4.25. Overcut

Above it was assumed that the wear ratio is determined by the overcut. Fig. 9 substantiates this assumption. At a constant current of 35 amps, but irrespective of frequency and duty cycle, wear ratio is seen to decrease with increasing overcut. With KK #8 as tool material, less than 1% wear ratio is obtained whenever the overcut is greater than 5×10^{-3} inches.

4.26. Size of Particles Eroded from the Cathode in Each Pulse

It was also assumed above that the overcut is governed by the size of the particles eroded from the workpiece in each pulse. Fig. 10 supports this assumption. One might then expect the overcut to be proportional to the diameter of these particles. If this is true, then the overcut should be proportional to the cube root of the volume of each particle, since the particles are spherical and volume $\sim$ (diameter)^3.

In calculating the volume of metal eroded in each pulse, 100% machinability was assumed throughout. Also, there is no reason why the metal eroded in each pulse should not come out as a number of separate particles rather than as one separate particle. In view of these facts the relationship is remarkable! The good agreement shown in Fig. 10 is probably due to the fact that the energy per pulse puts an upper bound on the size of the particles eroded, and the overcut is probably determined by the largest of these particles rather than by their average size. This correlation (Fig. 10) holds under all conditions tested!

From the above discussion one should expect a close correlation between the wear ratio and the volume of metal eroded per pulse. Fig. 11 bears out this expectation.

4.3. Conditions Determining Erosion Rate from the Workpiece

4.31. Frequency

A fairly flat peak in the erosion rate versus frequency curve (Fig.12) is obtained between 2 and 14 kc, at 35 amps and 50% duty cycle. For frequencies below 1 kc the erosion rate is seen to drop off substantially. It is believed that the main reason for this is unstable machining conditions. At frequencies above 20 kc the erosion rate drops off even more rapidly. At these high frequencies the ON-time for each pulse is quite short, and as discussed by De Nigris,[10] it takes a finite time to bring the machined surface up to melting temperatures. This is probably the main reason for the reduced erosion rate here.

4.32. Duty Cycle

At 9 kc and 35 amps there is no substantial variation of the erosion rate with duty cycle (Fig. 13). A slight reduction at very high and very low duty cycles can probably be attributed to unstable machining. Particularly low erosion rates are obtained at high duty cycles when hardened tool steel is machined (Fig. 13). The reason for this is not quite clear.

4.33. Current

The erosion rate, measured in units of in^3/min, increases with increasing current (Fig. 14). This is not surprising, since increasing the current means increasing the power input. However, the erosion rate in units of $in^3/(amp.min)$ decreases slightly with increasing current, when graphite electrodes are used (Fig. 15). With graphite as tool material it was impossible to achieve stable machining at currents above 70 amps. With copper electrodes currents up to 115 amps were obtained, but a substantial drop in the erosion "efficiency" (Fig. 15) occurs at about 60-70 amps. The principal cause for this is believed to be copper plating of the steel workpiece. Because of these high currents, the power density at the anode is now sufficient to create the anode vapor jets mentioned by Mandel'shtam and Raiskii,[5] but these jets do not substantially erode the cathode surface. Due to the large spacing they tend to plate onto the cathode, thereby reducing the effectiveness of the other cathode erosion mechanism (positive ion bombardment). This brings about the reduced erosion "efficiency" at high currents.

4.34. Tool Material

Figs. 12 through 15 consistently show that graphite tools give higher erosion rates under all conditions tested (except for the case of hardened steel (Fig. 12) which is not applicable in this comparison since no runs were made with copper tools on hardened steel). Of the graphite tool materials, the KK #12 gives slightly higher erosion rates than KK #8, but this difference is only of the order of a few percent. The main advantage of the KK #12 appears to be its greater strength and resistance to chipping, particularly in cases where fine detail on the tool is required. However, it is true that both slightly lower wear ratios and slightly higher erosion rates are obtained with this tool material.

4.4. Photomicrographs

At this point it appears profitable to take a close look at the photomicrographs in Figs. 17 through 22. These pictures support the theories presented. Under so-called "NO WEAR" conditions, which means low frequencies and high duty cycles, with small or zero wear ratio, the gap spacing between the tool and workpiece is always large. Under these conditions the "vapor jets" emitted from the cathode are ineffective in wearing down the tool. In fact, they tend to deposit, or plate, onto the tool and protect it from wear. Fig. 17 shows a blob of cathode metal on a copper tool, and Fig. 19 shows large splashes of cathode material on a graphite tool. The wear mechanism now has to remove this protective layer before the anode material can be worn away. This plating action is so effective that sometimes a negative wear ratio is obtained, due to a plating rate which is higher than the wear rate. The buildup on the tool is usually more pronounced in places where many sparks hit - in regions where the tool is usually worn most - near and at corners and edges. In Fig. 5 two distinct voltage lines are shown on the oscilloscope picture. Apparently one of these lines (No. 2) represents the potential drop across the gap when the arc is between steel on the cathode and copper (or graphite) on the tool, and the other line (No. 3) shows the potential when the arc is active between steel on the cathode and steel on the tool surface. This appears to be a reasonable deduction, but will be investigated further.

At higher frequencies tool wear can be considerable. Now the gap spacing is lower and the cathode jets are slowed down less before they strike the surface of the tool. This high-energy molten or vaporized metal will usually not deposit on the tool but will erode a crater there instead. The result is tool wear. Figure 18 shows such craters on a copper tool and in Fig. 20 some craters and a small steel deposit are shown on a graphite tool.

A large portion of the material eroded from the workpiece is carried away in the form of hollow spheres by the EDM fluid. Some of these spheres may also be found deposited on the tool (Fig. 21) or on the workpiece.

To get a closer look at these metal spheres, some of them were embedded in plastic and then polished. The result gave a cross-sectional view of the spheres, which indeed may be hollow (Fig. 22).

The fact that these spheres do exist, tends to support Zolotylch's[12] theory that the metal is primarily removed in molten form, rather than in the form of vapor (separate molecules). Zolotylch claims that most of the metal is removed from the workpiece after the arc is extinguished. This is not an impossible theory, since during the arc the pressure outside the surface reaches many atmospheres - a convincing argument for this is given by Holm[13] - and when the arc is shut off, the pressure in the arc suddenly drops to about 1 atmosphere. With respect to this new pressure, all the metal in the molten pool at the cathode surface finds itself superheated, and explodes violently. This may be the mechanism for creation of the "vapor jets" which wear down the anode, and is probably the source of the hollow spheres. However, more studies are required before this can definitely be pinned down as the mechanism of erosion.

5. SUMMARY

This investigation shows that graphite is a better tool material than copper for machining tool and die steel by EDM under conditions of reverse polarity. The wear ratio (tool/work) is found to increase with increasing frequency, and to decrease with increasing current or duty cycle. These results can all be explained through the concept of electrode spacing. At small spacings the vapor jets from the cathode erode the tool and bring about high wear ratios. At large spacings these same vapor jets tend to plate and protect the tool surface, giving rise to low wear ratios. The magnitude of the gap distance is controlled by the diameter of the largest particles eroded from the cathode, and this is in turn governed by the energy per pulse. Hence the wear ratio is essentially determined by the energy per pulse.

The erosion rate reaches a maximum value at frequencies from 1 to 14 kc, depending on the tool material. The duty cycle has little effect on the erosion rate; when the average current and the frequency are kept constant, a small peak is obtained at about 65% duty cycle. Erosion rate increases with current, as one might suspect, but for currents above 70 amps, with copper tools, substantial plating of the cathode surface occurs, thereby reducing the erosion rate.

It should be noted that a low frequency alone is not sufficient to guarantee a low wear ratio. If the current or the duty cycle is low enough, substantial tool wear will occur even at the lowest frequencies obtainable with today's EDM machines. Low wear ratios may be obtainable at higher frequencies if the gap spacing can be kept large enough.

6. RECOMMENDATIONS

This study shows that in order to obtain low wear ratios, it is essential to have large gap spacings. At the present time this is achieved mainly through the removal of large particles from the workpiece, at the expense of poor surface finish. Research should be done to find another way of maintaining large gap spacings, possibly through higher breakdown voltages, or EDM fluids with lower breakdown strengths, or both. Another possibility for maintaining large spacings might be to introduce artificially into the EDM fluid large conducting particles, so as to eliminate the need for removing large particles from the workpiece.

As a first step towards the above suggestions, a chamber will be constructed for the purpose of collecting and measuring all the particles formed during a machining test. Other variables to be investigated in the near future include the pressure, temperature, consistency, and volume flow rate of the EDM fluid. The effect of different workpiece materials will also be studied (currently in progress), to see if the theories suggested here are applicable over a wider range of conditions. The effect of duty cycle variation is still not fully understood, and will be further investigated, possibly by means of measuring the machinability. This may be done by comparing the average current (from the ammeter) with the peak current (from the scope); and the results can be checked by making use of an electronic counter to measure the actual number of pulses over a fixed period of time.

Surface damage to the workpiece has always been of great importance for some applications. Microcracks are often formed in the resolidified layer. This problem would be avoided if all the molten metal could be removed, rather than resolidified on the surface. It may be possible to achieve this through variations in the shape of the peak current profile. However, before this is attempted, a better model for the metal removal mechanism should be developed.

REFERENCES

1. Cook, N. H., Manufacturing Analysis, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts, 1965, pp. 121-126.

2. Berghausen, P. E., Brettschneider, H. D., and Davis, M. F., "Electro-Discharge Machining Program," Technical Documentary Report No. ASD-TDR-7-545 of the Cincinnati Milling Machine Co., Ohio, 1963.

3. Ullmann, W., "Electro-Erosive Metalworking-Theory and Practical Application of a Proved Method," Technische Rundschau No. 8, Feb. 28, 1958.

4. Webb, R. S., "High Voltage - Reverse Polarity EDM," Patent No. 3,158,728, filed July 26, 1960.

5. Mandel-shtam, S. L. and Raiskii, S. M., "Mechanism of Electro-erosion of Metals," Izvestiya Akad. Nauk SSSR, Ser. Fiz., Vol. 13, 1949, No. 5, pp. 549-565.

6. Kesaev, I. G., Cathode Processes in the Mercury Arc, Consultants Bureau, New York, 1964 (Russian Original, 1961), p. 29.

7. Holm, R., Electric Contacts Handbook, Springer-Verlag/Gottingen/Heidelberg, 1958, pp. 467-469.

8. Somerville, J. M., The Electric Arc, Barnes and Noble, Inc., New York, 1959, p. 66.

9. Kesaev, I. G., Cathode Processes in the Mercury Arc, Consultants Bureau, New York, 1964 (Russian Original, 1961), pp. 59-61.

10. De Nigris, E. G., "Heat Transfer Aspects of EDM," S.M. Thesis, M.I.T., August, 1967 (in preparation).

11. Livshits, A. L., Bannikov, G. K., and Sigarev, A. M., "High-Resistance Electrodes for Electro-Pulse Processing of Metals," Stanki-I-Instrument, Vol. 29, No. 5, 1958, pp. 23-25.

12. Zolotylch, B. N., "The Mechanism of Electro-Erosion of Metals in a Liquid Dielectric Medium," Problemy Elek. Obrabotki Materialov, 1960.

13. Holm, R., Electric Contacts Handbook, Springer-Verlag/Gottingen/Heidelberg, 1958, pp. 462-463.

APPENDIX A

DATA TABLES

TABLE 1-a: Tests using graphite Kost Kutter No. 8 tool and hardened steel H-13 workpiece.

Run No.	Frequency kc	Duty Cycle %	Current amps	Wear Ratio in^3/in^3	Erosion Rate $\frac{10^{-3} in^3}{min}$	Erosion Rate $\frac{10^{-4} in^3}{amp.min}$	Volume Eroded $\frac{10^{-8} in^3}{pulse}$	Overcut 10^{-3} in
1	0.41	80	35	-0.0067	6.8	1.94	28.6	9.5
2	0.81	80	35	-0.0026	8.05	2.01	16.5	8.5
5	9.14	77	35	0.0063	12.0	3.43	2.21	6.0
6	16.7	50	35	0.0696	14.3	4.08	1.42	3.1
8	63.2	32	11	0.228	1.20	1.14	0.032	1.3
10	0.34	50	23	0.0078	5.48	2.38	27.2	8.5
11	0.68	50	23	0.0029	6.83	2.97	16.2	7.3
12	1.40	50	35	0.0005	11.7	3.34	14.0	6.0
13	3.80	50	35	0.0141	16.2	4.63	7.08	5.5
14	8.5	50	35	0.0418	17.1	4.88	3.36	3.2
15	17.0	50	35	0.0598	16.1	4.02	1.57	3.0
16	33.6	50	23	0.117	9.0	3.91	0.447	1.5
17	6.8	12	1.2	0.319	0.39	3.25	0.096	1.5
18	7.6	30	35	0.0782	14.3	4.08	3.13	2.5
19	9.2	65	35	0.0316	19.7	5.63	3.56	4.5
20	9.0	50	11.5	0.0912	7.12	6.18	1.32	3.8
21	9.0	50	69	0.0133	28.5	4.13	5.27	3.5
25	9.0	50	23	0.0692	13.0	5.65	2.40	3.0
26	9.0	50	58	0.0205	25.3	4.37	4.67	4.0
29	8.4	50	1.2	0.16	0.207	1.72	0.041	1.8
30	9.0	50	46	0.029	22.1	4.81	4.10	3.8
33	9.6	40	35	0.0645	18.0	5.15	3.12	3.0
34	9.7	60	35	0.0311	19.0	5.43	3.26	4.0
35	9.5	70	35	0.0179	16.2	4.63	2.85	5.0

TABLE 1-b: Tests using graphite Kost Kutter No. 8 tool and unhardened steel H-13 workpiece.

Run No.	Frequency	Duty Cycle	Current	Wear Ratio	Erosion Rate	Erosion Rate	Volume Eroded	Overcut
	kc	%	amps	in^3/in^3	$\frac{10^{-3} in^3}{min}$	$\frac{10^{-4} in^3}{amp.min}$	$\frac{10^{-8} in^3}{pulse}$	10^{-3} in
B- 1	0.34	50	28	0.00625	10.2	3.64	49.6	8.5
B- 2	0.69	50	35	0.00385	13.5	3.86	32.4	7.5
B- 4	1.4	50	35	0.00276	15.0	4.28	18.2	8.2
B- 5	3.8	50	35	0.0241	17.2	4.92	7.58	4.8
B- 6	9.6	50	35	0.0554	17.4	4.97	3.02	2.8
B- 8	30	50	23	0.123	10.6	4.61	0.54	2.0
B- 9	17	50	35	0.0696	17.9	5.11	1.77	2.7
B-10	60	35	11.5	0.179	2.20	1.91	0.056	1.2
B-11	8.6	30	35	0.0827	15.0	4.28	2.91	2.7
B-12	9.0	40	35	0.0765	21.0	6.0	3.88	3.7
B-13	9.3	50	35	0.0533	16.7	4.77	2.95	4.3
B-14	9.4	55	35	0.0557	20.5	5.85	3.62	3.5
B-16	8.9	65	35	0.0338	21.5	6.15	4.03	4.8
B-17	9.3	70	35	0.0237	20.6	5.89	3.68	4.3
B-19	9.8	77	35	0.0178	18.1	5.17	3.08	4.6
B-20	9.3	60	35	0.0466	21.7	6.20	3.89	3.9
B-21	8.6	50	11.5	0.0828	7.60	6.60	1.47	3.9
B-22	8.6	50	17	0.0756	9.95	5.85	1.93	3.3
B-23	8.7	50	23	0.0712	13.8	6.00	2.63	3.4
B-24	8.7	50	29	0.0690	17.4	6.00	3.33	3.5
B-25	8.9	50	35	0.0496	18.6	4.65	3.47	3.4
B-26	8.9	50	46	0.0404	25.0	5.43	4.65	3.5
B-27	9.2	50	58	0.0214	26.2	4.52	4.66	3.8
B-29	9.2	50	1.2	0.161	0.189	1.57	0.034	2.2
B-31	9.2	50	69	0.0205	32.5	4.72	5.85	4.2
B-32	9.1	50	7	0.0942	4.56	6.52	0.833	3.5

TABLE 2: Test using graphite Kost Kutter No. 12 tool and unhardened steel H-13 workpiece.

Run No.	Frequency kc	Duty Cycle %	Current amps	Wear Ratio in^3/in^3	Erosion Rate $\frac{10^{-3} in^3}{min}$	Erosion Rate $\frac{10^{-4} in^3}{amp.min}$	Volume Eroded $\frac{10^{-8} in^3}{pulse}$	Overcut 10^{-3}in
201	0.33	50	35	0.0055	11.85	3.39	59.0	10.3
202	0.68	50	35	0.0	14.25	4.07	34.8	9.0
203	1.4	50	35	0.00076	16.35	4.67	20.1	7.5
204	3.9	50	35	0.0240	19.2	5.48	8.14	4.3
206	17	50	35	0.0547	14.1	4.03	1.39	2.8
207	32	50	23	0.104	10.4	4.52	0.542	2.2
208	63	38	1.2	0.324	0.461	3.84	0.0122	1.5
209	8.3	30	35	0.0728	14.2	4.06	2.84	3.5
210	8.3	35	35	0.0618	15.6	4.46	3.11	3.5
211	8.2	40	35	0.0667	20.7	5.92	4.21	4.2
212	8.6	45	35	0.0467	16.9	4.83	3.28	3.7
213	8.6	50	35	0.0440	17.9	5.12	3.50	3.5
214	8.7	55	35	0.0437	21.2	6.05	4.05	4.7
215	9.0	60	35	0.0407	21.4	6.12	3.94	4.5
216	8.7	65	35	0.0325	22.2	6.34	4.25	5.0
217	8.6	70	35	0.0173	21.0	6.00	4.07	6.1
218	8.6	78	35	0.0143	20.7	5.92	4.03	6.5
219	7.5	50	7	0.0851	4.72	6.75	1.05	4.0
220	7.5	50	9.2	0.0838	5.93	6.45	1.32	4.2
221	7.9	50	11.5	0.0814	7.24	6.29	1.52	4.5
222	8.0	50	17	0.0744	10.7	6.30	2.23	4.2
223	8.1	50	23	0.0666	14.9	6.48	3.06	4.3
224	8.1	50	29	0.0618	18.7	6.45	3.85	4.8
225	8.0	50	35	0.0412	17.9	5.12	3.74	4.1
226	8.1	50	46	0.0361	27.1	5.90	5.57	5.0

TABLE 3: Tests using copper tool and unhardened steel H-13 workpiece.

Run No.	Frequency kc	Duty Cycle %	Current amps	Wear Ratio in^3/in^3	Erosion Rate $\frac{10^{-3} in^3}{min}$	Erosion Rate $\frac{10^{-4} in^3}{amp.min}$	Volume Eroded $\frac{10^{-8} in^3}{pulse}$	Overcut 10^{-3}in
52	0.34	50	38	0.254	9.6	2.5	47.6	7.0
53	0.68	50	36	0.252	11.6	3.3	28.2	7.0
54	1.3	50	36	0.324	13.7	3.9	17.3	7.2
55	3.9	50	38	0.440	13.5	3.8	5.72	4.8
56	9.3	50	36	0.514	12.9	3.6	2.32	2.5
57	17	50	36	0.391	12.8	3.6	1.29	3.8
58	33	50	18.4	0.468	5.9	3.2	0.30	2.5
62	17	50	36	0.320	12.1	3.4	1.21	4.5
65	9.3	60	36	0.438	13.8	3.9	2.48	3.8
66	9.9	78	36	0.350	14.1	4.0	2.38	4.5
67	8.8	50	35	0.504	12.5	3.6	2.37	3.0
68	8.7	40	36	0.498	13.5	3.8	2.58	3.0
69	9.8	70	36	0.373	13.5	3.7	2.29	4.8
71	9.3	70	36	0.376	14.4	4.1	2.58	3.0
72	8.2	35	35	0.467	14.8	4.2	3.00	3.5
73	8.7	45	35	0.492	12.0	3.4	2.30	3.2
74	8.7	30	36	0.473	13.9	3.9	2.85	2.5
75	8.7	50	70	0.450	22.2	3.2	4.25	2.25
76	8.7	50	93	0.450	23.5	2.5	4.51	2.5
78	8.8	50	23	0.517	9.6	4.2	1.83	3.0
79	8.9	50	115	0.432	24.6	2.1	4.58	3.0
80	8.9	50	11.5	0.527	3.7	3.2	0.69	3.8
81	8.5	30	35	0.587	12.3	3.5	2.43	3.5
85	9.1	50	11.5	0.540	4.0	3.5	0.73	4.5
86	9.0	50	58	0.362	23.1	4.0	4.27	4.5
87	9.0	50	17.5	0.562	5.9	3.2	1.09	4.5
89	8.5	40	36	0.487	14.5	4.1	2.95	4.0
90	8.3	35	35	0.489	14.4	4.1	2.91	4.4
91	17	50	35	0.391	13.8	4.0	1.37	3.8
93	0.67	50	35	0.297	17.1	4.9	42.7	9.3
95	8.4	50	35	0.532	13.0	3.7	2.58	4.0
96	7.3	30	35	0.626	9.6	2.7	2.20	3.8
98	7.0	50	47	0.371	19.6	4.2	5.64	6.5

APPENDIX B

GRAPHS AND PHOTOMICROGRAPHS

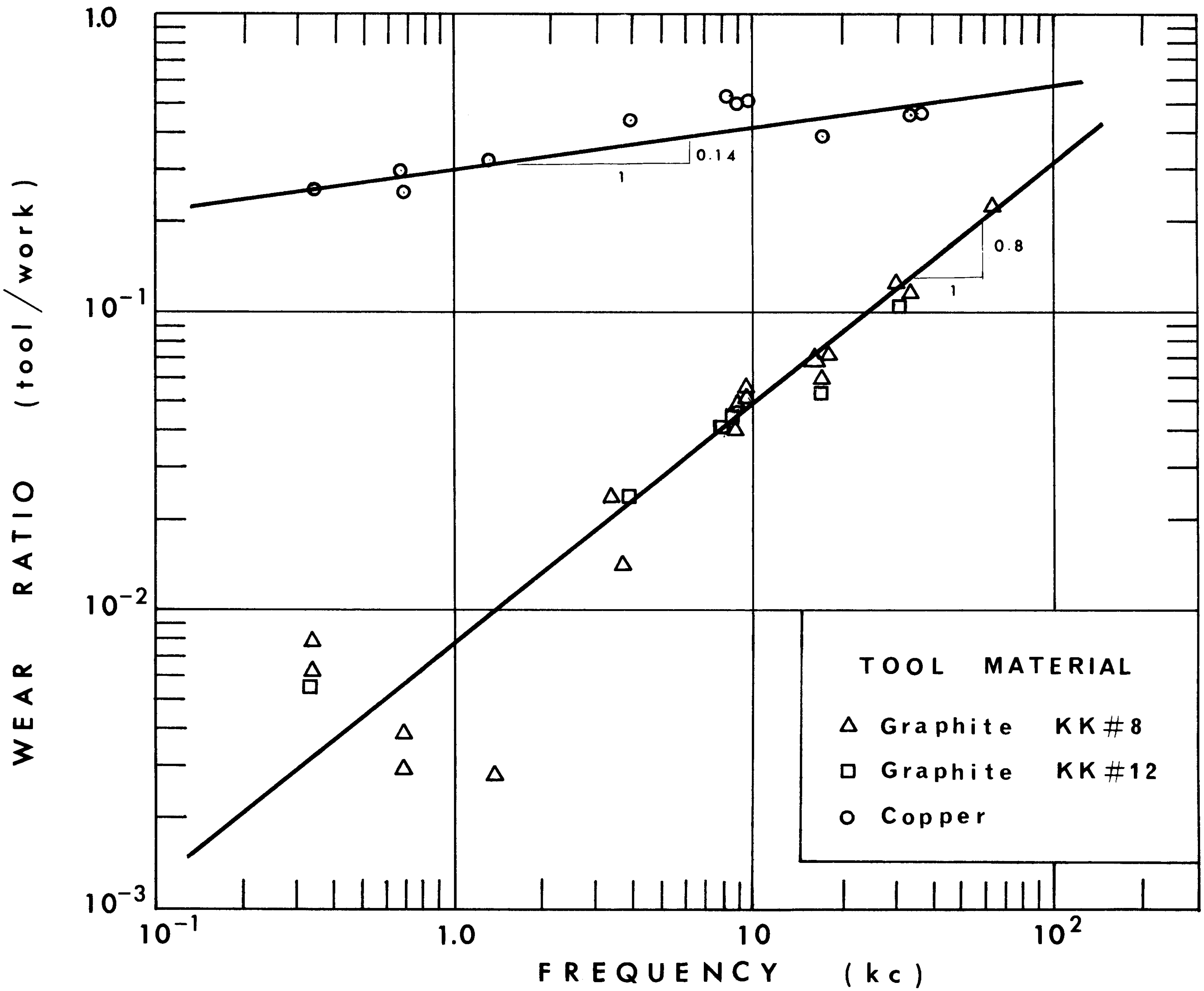

Fig. 6. Dependence of wear ratio on frequency at a current of 35 amps and a duty cycle of 50%.

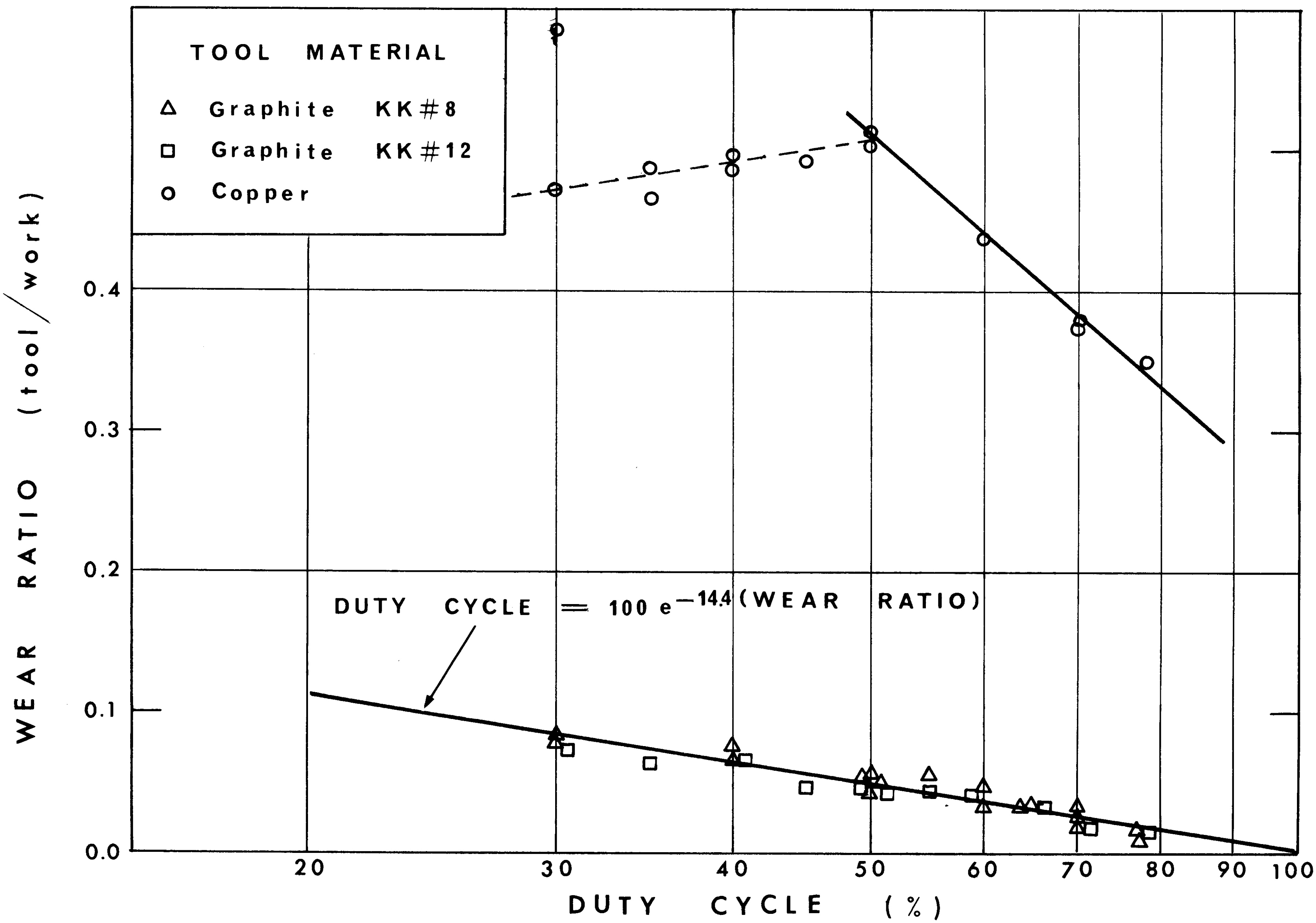

Fig. 7. Dependence of wear ratio on duty cycle at a frequency of 9 kc and a current of 35 amps.

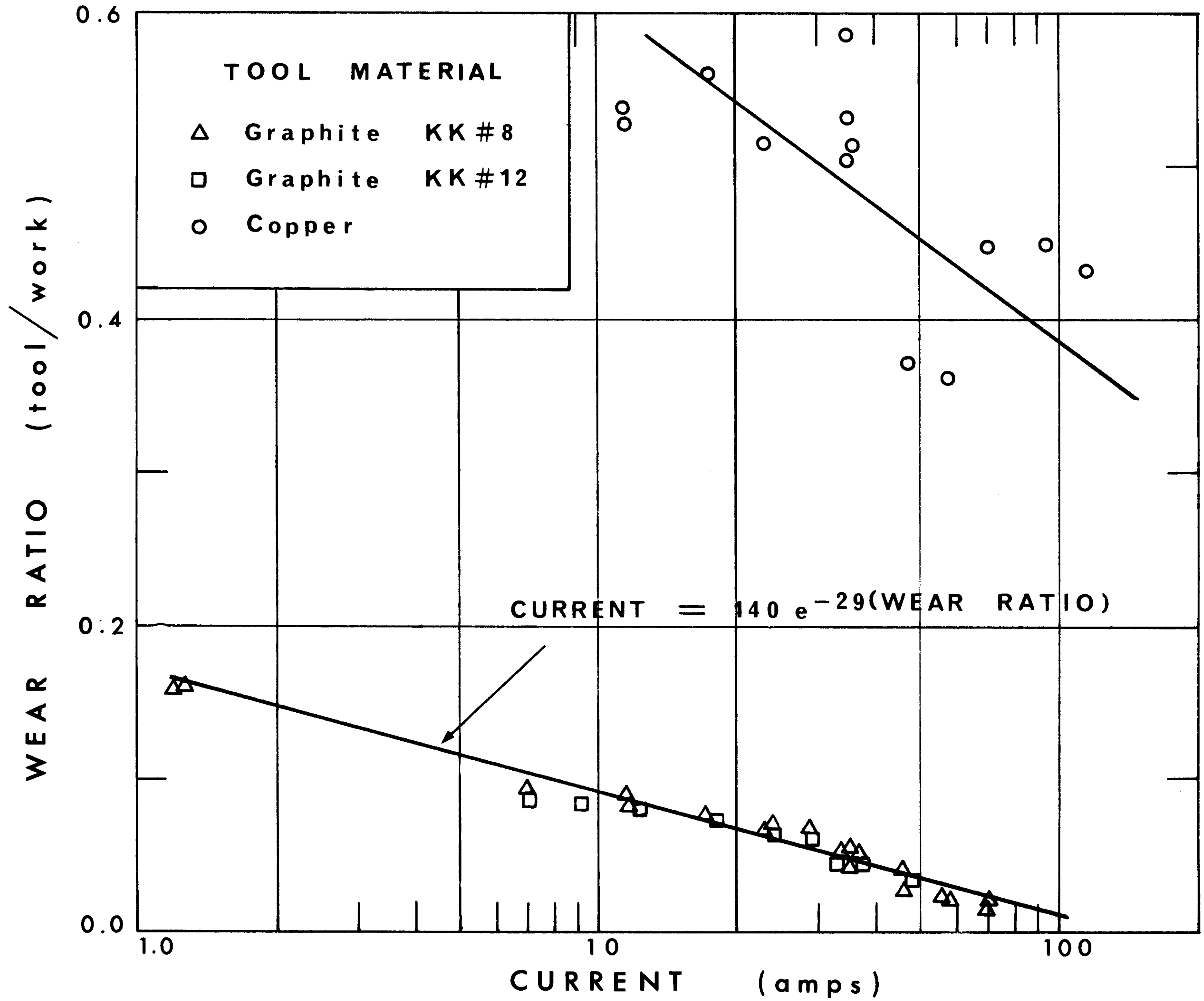

Fig. 8. Dependence of wear ratio on current at a frequency of 9 kc and a duty cycle of 50%.

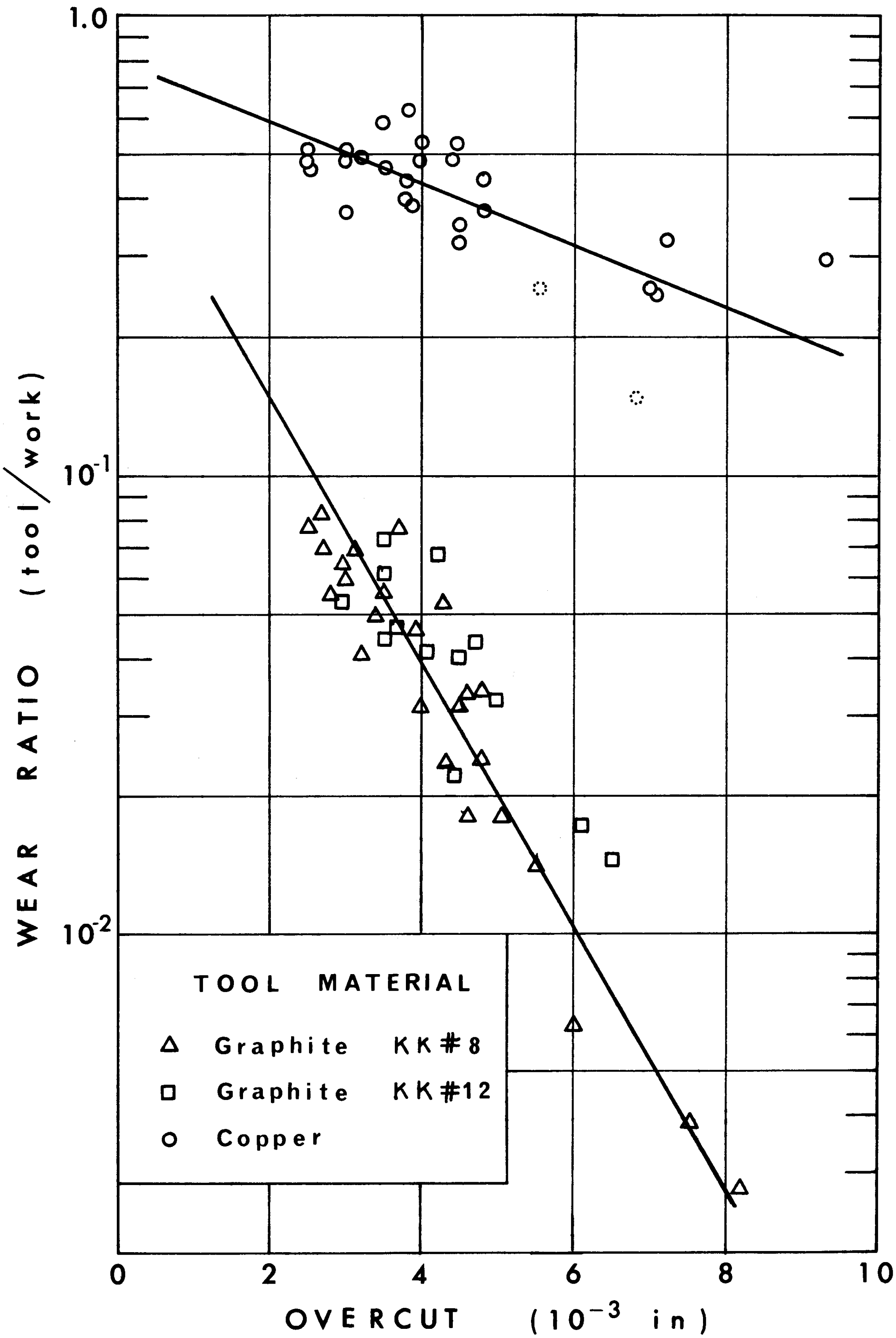

Fig. 9. Dependence of wear ratio on overcut at a current of 35 amps (all frequencies and duty cycles).

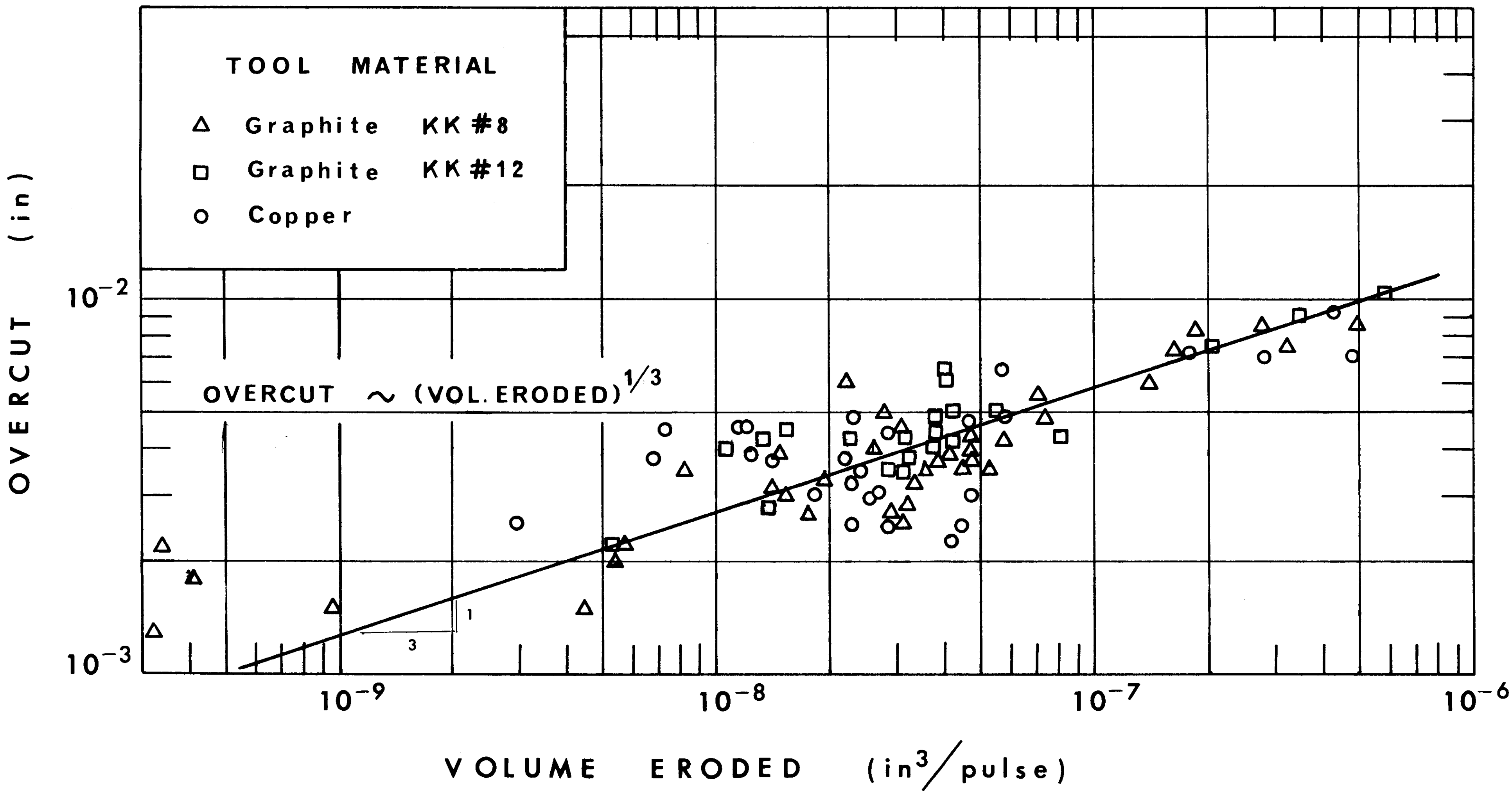

Fig. 10. Dependence of overcut on the volume of metal eroded from the workpiece in each pulse (for all frequencies, duty cycles, currents, and tool materials).

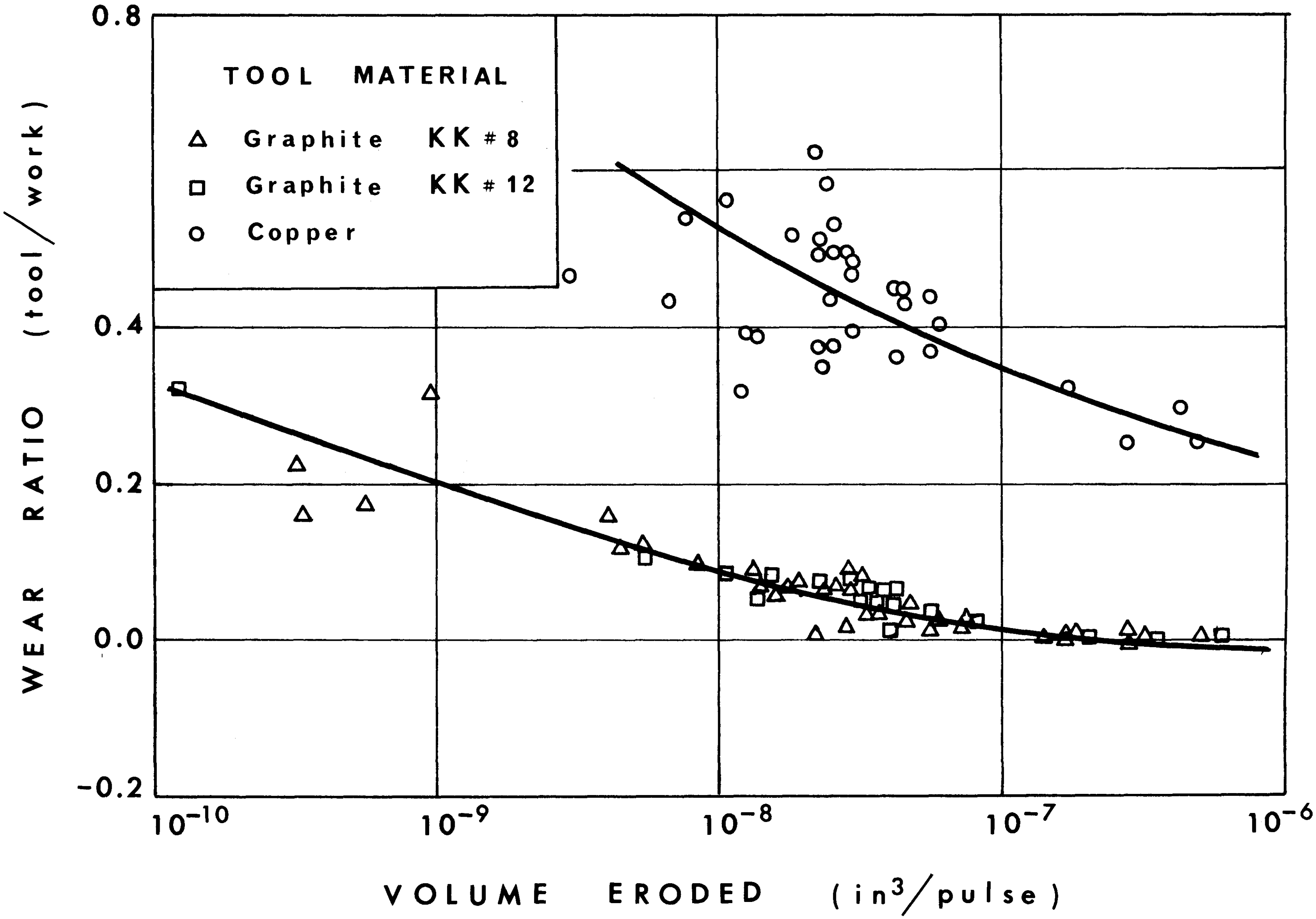

Fig. 11. Dependence of wear ratio on the volume of metal eroded from the workpiece in each pulse (for all frequencies, duty cycles, and currents).

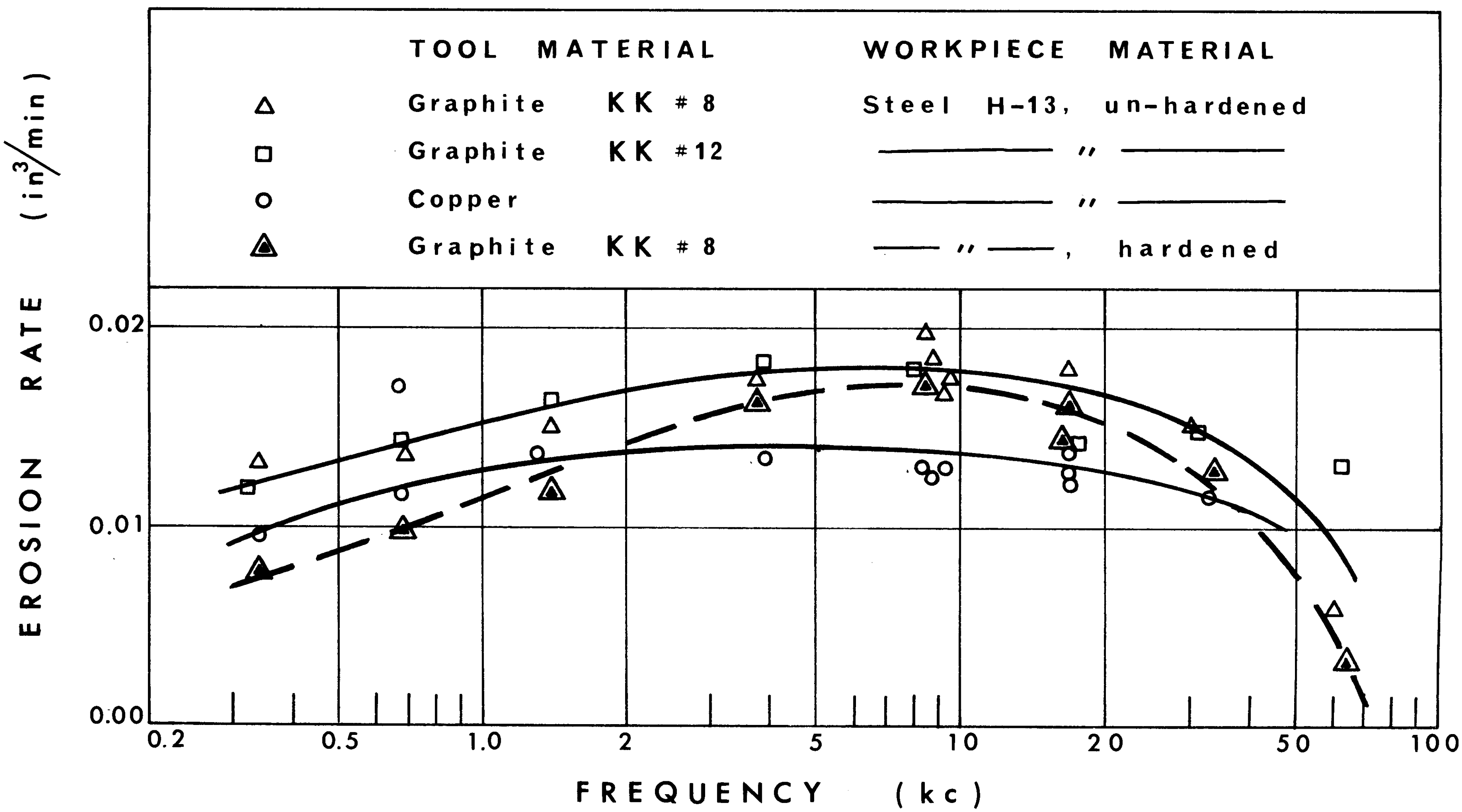

Fig. 12. Dependence of erosion rate on frequency at a current of 35 amps and a duty cycle of 50%. [Some of these runs were made at lower currents and then corrected to 35 amps using Eq.(8).]

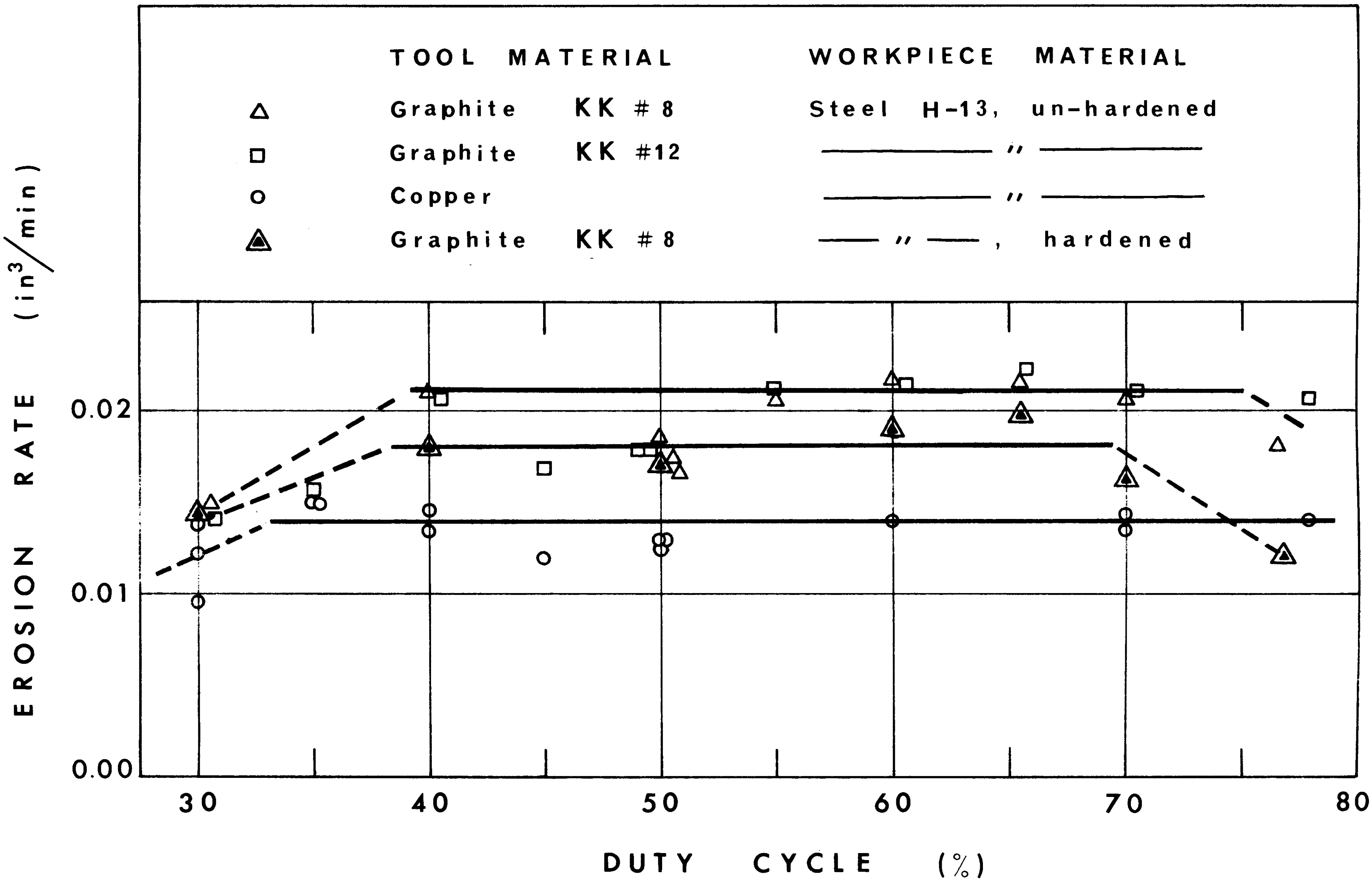

Fig. 13. Dependence of erosion rate on duty cycle at a frequency of 9 kc and a current of 35 amps.

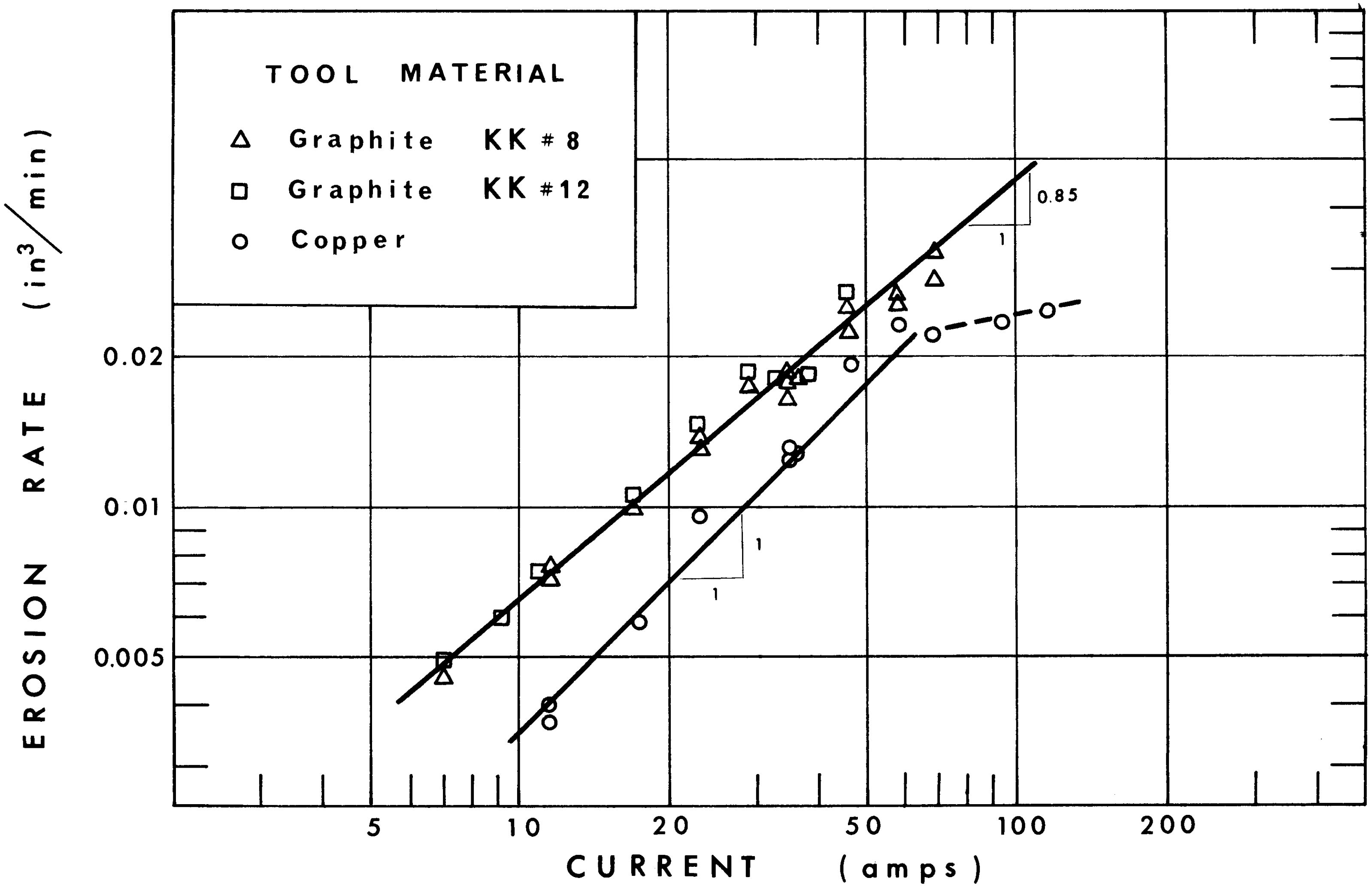

Fig. 14. Dependence of erosion rate on machining current at a frequency of 9 kc and a duty cycle of 50%.

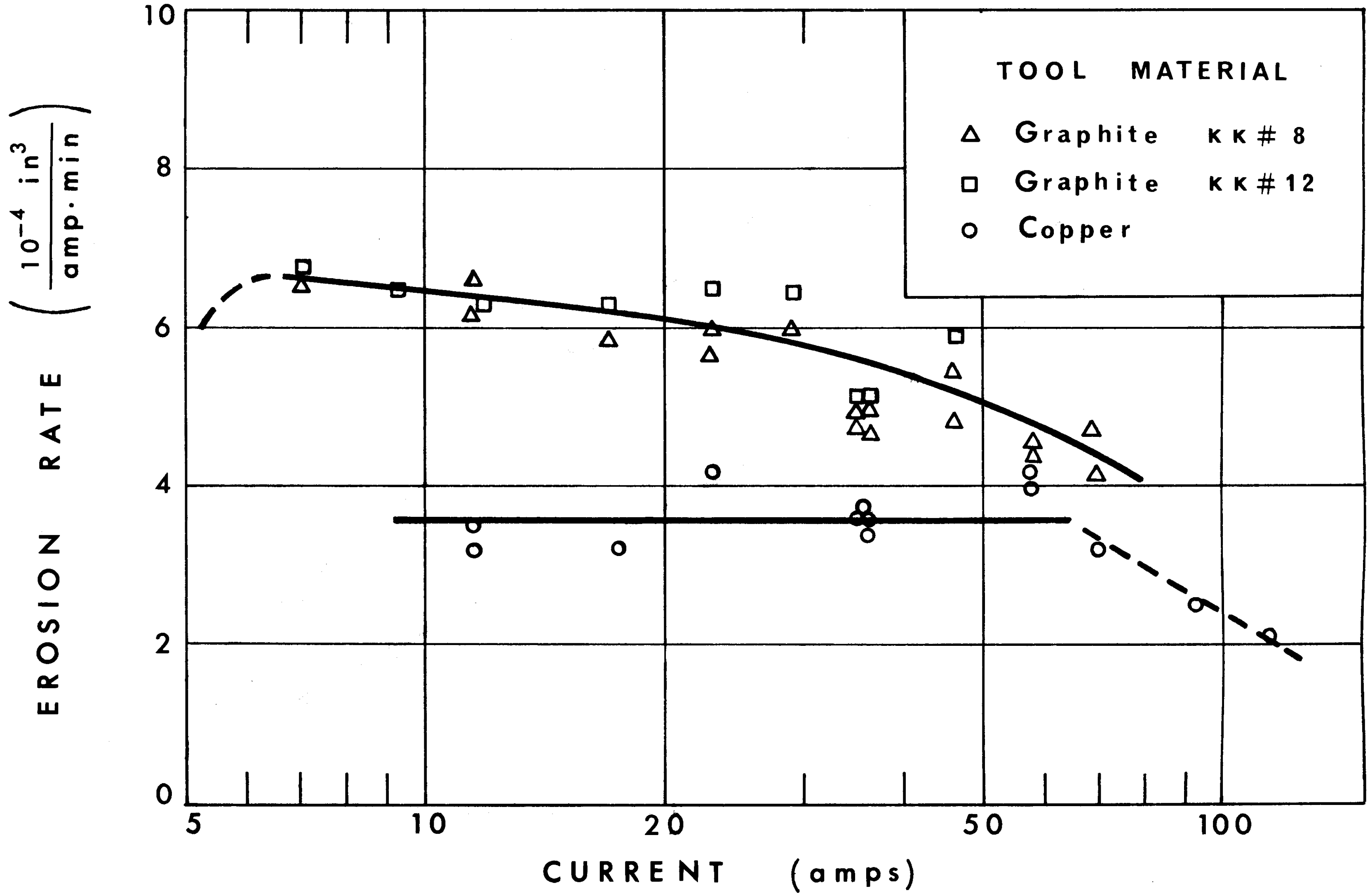

Fig. 15. Dependence of erosion rate $\left(\frac{10^{-4}\ in^3}{amp.min}\right)$ on current at a frequency of 9 kc and 50% duty cycle.

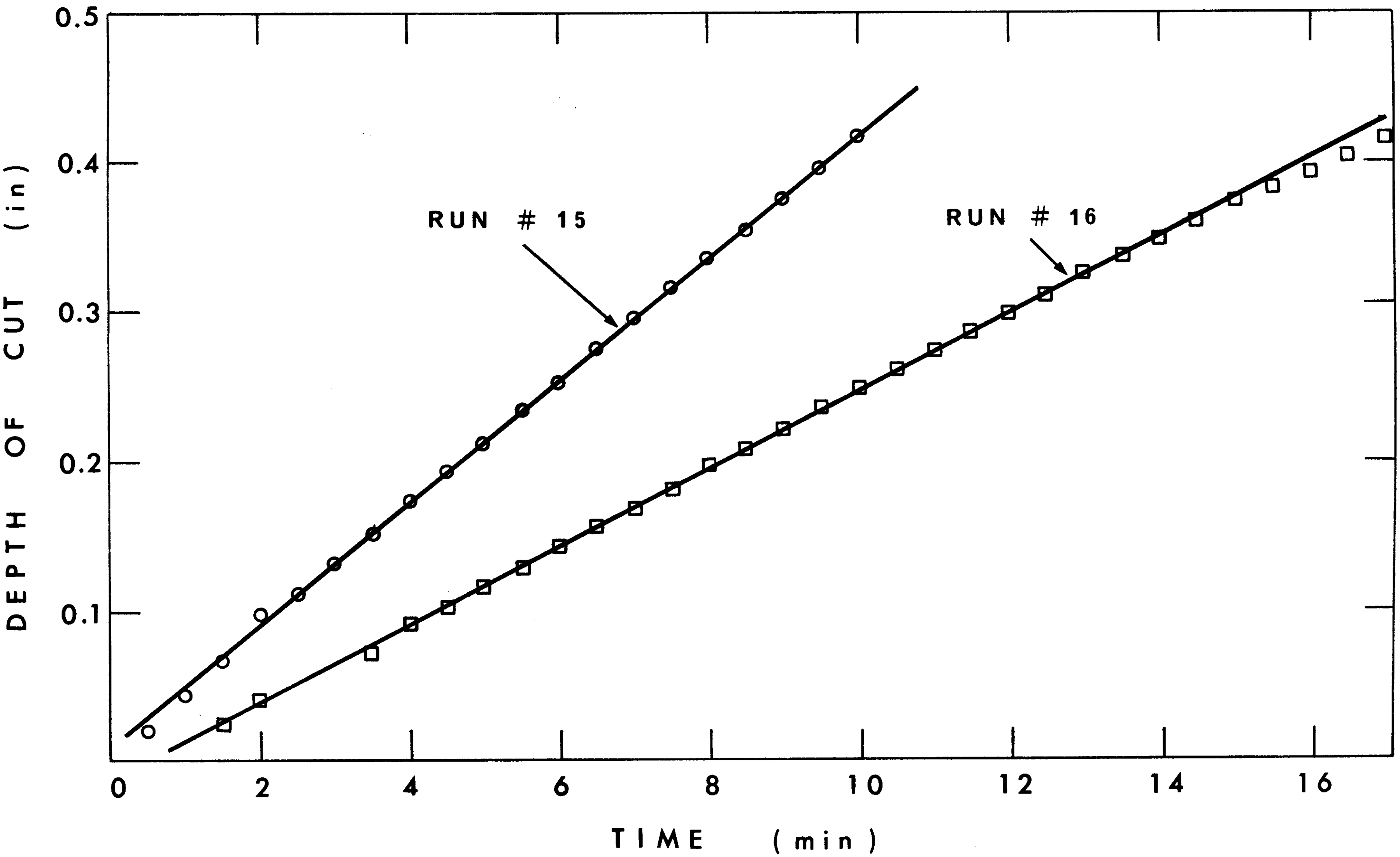

Fig. 16. Erosion rate does not depend on the depth of cut in the region tested.

Fig. 17. Photomicrograph (100x), showing copper tool with steel deposit from workpiece. Note that no serious damage to tool occurred (low frequency conditions, 1 kc).

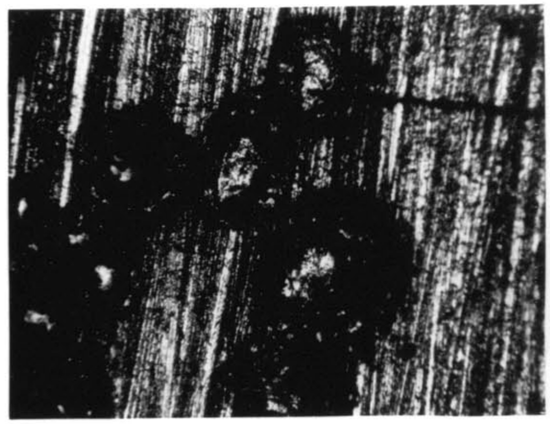

Fig. 18. Photomicrograph (100x), showing copper tool with erosion craters (high frequency conditions, 68 kc).

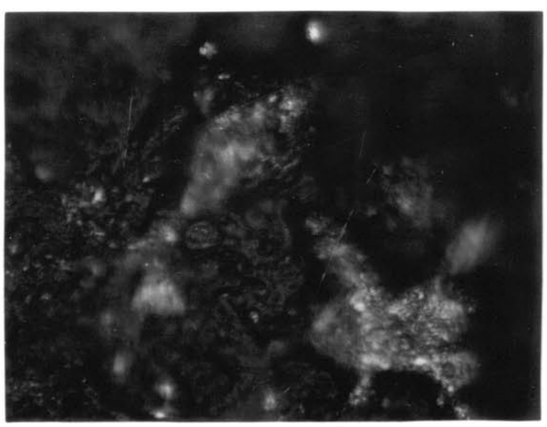

Fig. 19. Photomicrograph (500x), showing graphite tool with large protective splashes of steel from workpiece (low frequency conditions, 0.34 kc).

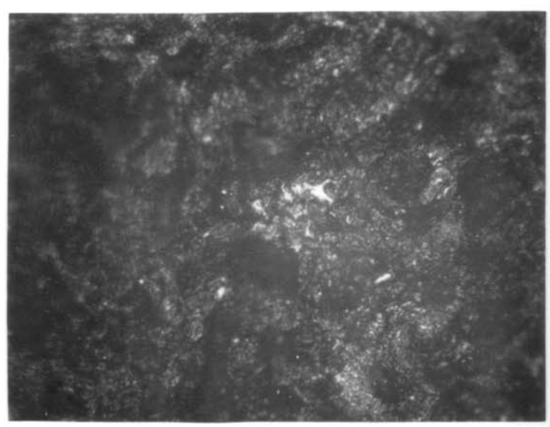

Fig. 20. Photomicrograph (200x), showing graphite tool with slight steel deposit, offering very little protection to tool (high frequency conditions, 63 kc).

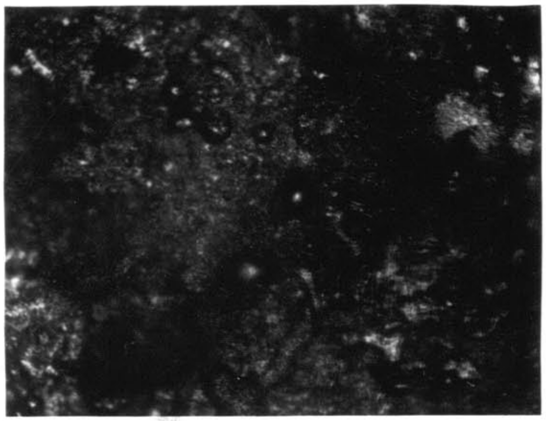

Fig. 21. Photomicrograph (100x), showing graphite tool covered with splashes of steel and hollow steel spheres (low frequency conditions, 0.34 kc).

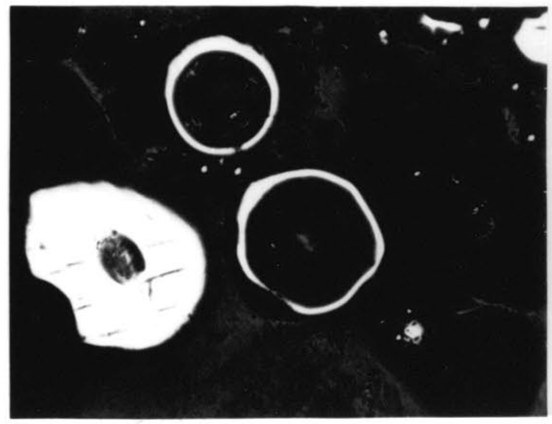

Fig. 22. Photomicrograph (100x), showing steel spheres from EDM fluid. This cross-sectional view clearly shows that at least some of the spheres are hollow.